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Description

[*REAL-TIME MONITORING AND CONTROL OF RESERVOIR FLUID SAMPLE CAPTURE*]

BACKGROUND OF INVENTION

[0001] The invention relates to methods and apparatus for sampling reservoir fluid.

[0002] A reservoir is a rock formation in which fluids, e.g., hydrocarbons such as oil and natural gas and water, have accumulated. Due to gravitational forces, the fluids in the reservoir are segregated according to their densities, with the lighter fluid towards the top of the reservoir and the heavier fluid towards the bottom of the reservoir. One of the main objectives of formation testing is to obtain representative samples of the reservoir fluid. Commonly, reservoir fluid is sampled using a formation tester, such as the Modular Formation Dynamics Tester (MDT), available from Schlumberger Technology Corporation, Houston, Texas. In practice, the formation tester is conveyed,

generally on the end of a wireline, to a desired depth in a borehole drilled through the formation. The formation tester includes a probe that can be set against the borehole wall, allowing reservoir fluid to be drawn into a flow line in the formation tester. The formation tester also includes a pump and one or more sample chambers. Typically, optical fluid analyzers are inserted into the flow line of the formation tester to monitor the fluid(s) flowing in various locations of interest. For example, an optical analyzer is often run directly above the probe to monitor the type of fluid entering the flow line.

[0003] Initially, the fluid drawn into the flow line is a mixture of reservoir fluid and mud filtrate. To obtain a sufficiently high quality fluid sample, a cleanup step in which mud filtrate is purged from the flow line is performed. This step involves pumping fluid through the flow line and out into the well. As pumping continues, more and more of the reservoir fluid is consumed around the inlet of the probe. Eventually, a fluid mixture that is more representative of the reservoir fluid starts to enter the flow line. Optical fluid analyzers are used to monitor the content of the fluid entering the flow line and how the fluid proceeds through the tool. When the mud filtrate content of the

fluid entering the flow line is reduced to an acceptable level, the sample chamber is opened and fluid in the flow line is pumped into the sample chamber. Usually, the following ancillary objectives are set for this step: (1) that a certain minimum volume of reservoir fluid be captured, and (2) that the reservoir fluid captured be single hydrocarbon phase, e.g., oil phase or gas phase, but not both. Finally, the sample chamber is closed and returned to the surface.

[0004] In practice, there is only a certain maximum time allowed before the cleanup step must be terminated. Therefore, there is no guarantee that the fluid mixture in the flow line is adequately decontaminated prior to being captured in the sample chamber. Further, the sample chamber may be returned to the surface without a sample, e.g., because the sample chamber was not opened successfully. Further, the sample chamber may be returned to the surface unclosed, e.g., because the sample chamber was not successfully closed after the fluid sample was collected. In this case, the content of the sample chamber may be lost or exposed to contaminants or undergo a phase change as it is returned to the surface. Prior to the present invention, the inventors are not aware of methods for verifying

in real-time that the three steps described above, i.e., cleanup, sample capture, and sample chamber closing, are successfully accomplished before the sample chamber is retrieved to the surface.

[0005] From the foregoing, there is desired a method of assuring quality fluid sample capture from a reservoir.

SUMMARY OF INVENTION

[0006] In one aspect, the invention relates to a method of sampling reservoir fluid which comprises establishing communication between a reservoir and an entry port of a flow line disposed in a borehole penetrating the reservoir, separating fluid received in the entry port into individual fluid components and sequentially flowing slugs of each individual fluid component along the flow line, observing the slugs as they move along the flow line in order to determine the composition of the slugs, estimating when a desired slug containing a sufficient volume of desired fluid component would be in the vicinity of a sample chamber in the flow line, and opening the sample chamber to capture the desired slug when the desired slug is in the vicinity of the sample chamber.

[0007] In another aspect, the invention relates to a system for sampling reservoir fluid which comprises a tool body hav-

ing a flow line with an entry port and an exit port and being adapted to be suspended in a borehole penetrating a reservoir. The system includes a fluid separator installed in the flow line for separating fluid received from the entry port into individual fluid components and sequentially outputting slugs of each individual fluid into the flow line. The system includes a fluid analyzer installed in the flow line downstream of the fluid separator for determining the composition of the slugs as they move along the flow line. The system includes at least one sample chamber in the flow line downstream of the fluid analyzer for capturing a desired slug containing a desired fluid component.

[0008] Other features and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of Drawings

[0009] Figure 1 is a simplified diagram of a downhole tool for sampling reservoir fluid in accordance with one embodiment of the invention.

[0010] Figures 2A and 2B are schematic illustrations of a dual-displacement pump.

[0011] Figure 3 shows an example of an output of the dual-displacement pump of Figures 2A and 2B.

[0012] Figure 4 shows flow line behavior before sample capture.

[0013] Figure 5 shows flow line behavior after sample capture.

[0014] Figure 6 shows flow line behavior during verification of sample chamber closure.

DETAILED DESCRIPTION

[0015] The invention will now be described in detail with reference to a few preferred embodiments, as illustrated in accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the invention may be practiced without some or all of these specific details. In other instances, well-known features and/or process steps have not been described in detail in order to not unnecessarily obscure the invention. The features and advantages of the invention may be better understood with reference to the drawings and discussions that follow.

[0016] Figure 1 shows a simplified diagram of a downhole tool *100* for sampling reservoir fluid in accordance with one embodiment of the invention. The downhole tool *100* is conveyed to a selected depth in a borehole *102* drilled

through a rock formation *104* using, for example, a wire-line 1*06*. The downhole tool *100* includes a flow line *108* having an entry port *110* and an exit port *112*. A probe assembly *114*, such as the Single-Probe Module or Dual-Probe Module included in the Schlumberger MDT or described in U.S. Patents 4,860,581 and 6,058,773, both assigned to Schlumberger Technology Corporation, may be mounted at the entry port *110*. The probe assembly *114* can be extended to and set against the borehole wall *116* so that reservoir fluid in the formation *104* can be drawn into the entry port *110*. Although not shown, a packer assembly, such as the Dual-Packer Module included in the Schlumberger MDT or described in U.S. Patent No. 4,860,581, may be installed below the probe assembly *114*. The packer assembly may be inflated against the borehole wall *116* to isolate an interval of the formation *104* to be tested.

[0017] The downhole tool *100* includes a pump *200*, such as the Pump-Out module included in the Schlumberger MDT or described in U.S. Patent Nos. 4,860,581 and 6,058,773, installed above the probe assembly *114*. In the following discussion, the portion of the flow line *108* between the entry port *110* and the pump *200* will be referred to as the

inlet flow line *108a*, and the portion of the flow line *108* between the pump *200* and the exit port *112* will be referred to as the outlet flow line *108b*. The downhole tool *100* further includes a fluid type analyzer *120*, such as the Live Fluid Analyzer (LFA) included in the Schlumberger MDT, installed above the pump *200*. The fluid type analyzer *120* analyzes the output of the pump *200* as opposed to the input to the pump *200* as done in conventional formation testing. The downhole tool *100* further includes at least one sample chamber *122*, such as the Modular Sample Chamber, Multi-Sample module, or Single-Phase Multi-Sample Chamber included in the Schlumberger MDT. Other components necessary to make the downhole tool *100* fully functional, such as a power cartridge, which are not shown are within the purview of one skilled in the art. The wireline *106* may be used to transmit data to the surface.

[0018] In one embodiment, the pump *200* is a dual-displacement pump. The function of the dual-displacement pump *200* is two-fold. One function is to pump fluid into or out of the flow line *108* or into or out of the sample chamber *122*. The second function is to separate a fluid mixture received in the inlet flow line *108a* into individual fluids ac-

cording to the density of the individual fluids and then sequentially output slugs of these individual fluids into the outlet flow line *108b*, where the slugs move like a train along the outlet flow *108b*. In this way, a slug containing a desired fluid (such as a hydrocarbon) can be captured into the sample chamber *122* while slugs containing unwanted fluid (such as mud filtrate) can be allowed to exit the outlet flow line *108b* through the exit port *112*. The dual-displacement pump *200* can create trains of slugs of individual fluids in a predictable pattern because fluid separation occurs in each cycle of the pump. However, the invention is not limited to use of a dual-displacement pump as a fluid separator. In general, any device that can separate a fluid mixture into individual fluids and create slugs of these individual fluids in a predictable pattern can be used in the invention. An example of a down hole fluid separator is any chamber that has a significantly larger diameter than the diameter of the flow line *108*. The chamber would be placed somewhere in the flow line *108* (before the fluid analyzer *120*). The fluid mixture would enter the chamber from the flow line which is attached to the bottom of the chamber. Fluid phases of different density would segregate in the chamber, and the separated

mixture would leave from the top of the chamber into the flow line. The segregation causes the fluids to leave as a train of slugs. It should be noted that if the fluid separator is not a pump, a pump would still be needed to pump fluid into and out of the flow line *108* or into and out of the sample chamber *122*.

[0019] Figure 2A shows the pump *200* configured as a dual-displacement pump. In this embodiment, the pump *200* includes hydraulic cylinders *202*, *204*. The pistons *206*, *208* of the hydraulic cylinders *202*, *204*, respectively, are coupled together so that they move concurrently. The hydraulic cylinders *202*, *204* have pump chambers *202a*, *204a*, which can be selectively connected to the inlet flow line *108a* to receive fluid or the outlet flow line *108b* to dispense fluid. Inlet check valves *210a* and outlet check valves *210b* control which of the flow lines *108a*, *108b* is in communication with the pump chambers *202a*, *204a* at any time. The hydraulic cylinders *202*, *204* also have hydraulic fluid chambers *202b*, *204b*, which are in communication with a hydraulic fluid source *212*. Hydraulic fluid is alternately supplied to the hydraulic fluid chambers *202b*, *204b* to either move the pistons *206*, *208* downwardly (down-stroke) or upwardly (up-stroke). The dual-

displacement pump arrangement eliminates refill dead time by refilling one of the hydraulic cylinders *202*, *204* with fluid while the other hydraulic cylinder is dispensing fluid.

[0020] During the down-stroke cycle, hydraulic fluid is supplied to the hydraulic fluid chamber *202b*, forcing the pistons *206*, *208* to move downwardly. As the pistons *206*, *208* move downwardly, slugs of fluids are dispensed from the pump chamber *202a* into the outlet flow line *108b* while the pump chamber *204a* is filled with fluid from the inlet flow line *108a*. The fluid admitted into the pump chamber *204a* is usually a mixture of fluids, such as hydrocarbons, water, and mud filtrate. Due to gravity, the fluid in the pump chamber *204a* separates into individual fluids, with the lighter fluid towards the top of the chamber and the heavier fluid towards the bottom of the chamber. To allow mud filtrate to form a distinct layer from hydrocarbons, the mud filtrate is preferably water-based as opposed to oil-based. During the up-stroke cycle, as shown in Figure 2B, hydraulic fluid is supplied to the hydraulic fluid chamber *204b*, forcing the pistons *206*, *208* to move upwardly. As the pistons move upwardly, the separated fluids in the pump chamber *204a* are dispensed into the outlet flow line

108b, one individual fluid at a time. The individual fluids are dispensed as slugs. While the pump chamber *204a* is dispensing, the pump chamber *202a* is filled with fluid from the inlet flow line *108a*.

[0021] Each cycle of the dual-displacement pump *200* results in fluid separation. Thus, slugs of individual fluids are continuously dispensed from the pump *200* into the outlet flow line *108b* in a predictable manner. For illustrative purposes, Figure 3 shows slugs, generally indicated at *300*, leaving the pump. The pump stroke direction when the slugs *300* were produced is indicated in the figure. Two main volume slugs *302a*, *302b*, each main volume corresponding to an individual fluid, are shown for each pump stroke. At the beginning of each down-stroke and up-stroke of the pump is a dead volume slug *304a*, *304b*, respectively. The dead volume is the section of outlet flow line (*108b* in Figures 2A, 2B) between the port of each pump chamber (*202a*, *204a* in Figures 2A, 2B) and the output check valve (*210b* in Figures 2A, 2B). The dead volume *304a* at the beginning of each down-stroke contains the last fluid pumped out from the previous up-stroke of the pump. If the fluid in the pump chamber *202a* contains gas, the dead volume *304a* would be gas. The dead volume

304a can be a good indicator of whether any gas flows out of the pump, especially when there is very little gas flow.

[0022] Returning to Figure 1, since fluid leaves the pump *200* as slugs of individual fluids *300*, an operator at the surface can advantageously time opening of the sample chamber *122* such that as much as possible of one of the slugs *300* containing a desired fluid can be captured. In order to do this, the operator needs to know when the slug containing the desired fluid is leaving the pump *200*. This is accomplished by observing over a time period the pattern in which slugs are outputted from the pump. To do this, the slugs *300* leaving the pump *200* are passed through the fluid type analyzer *120*. The fluid type analyzer *120* may include a gas detector, e.g., a gas refractometer, to distinguish between a liquid phase and a gas phase and/or a liquid detector, e.g., an optical absorption spectrometer, to distinguish between liquid and/or gas phases. As the slugs *300* pass through the fluid type analyzer *120*, the fluid type analyzer *120* generates an output, such as an absorption spectra, that can be used to determine the composition of the slugs passing through it. Figure 4 shows an example of flow (indicated at *400*) detected by the fluid type analyzer *120* prior to sample capture. Oil

slugs *402* and water slugs *404* are shown. Oil and water are reliably detected by their different absorption spectra. The fluid (slug) volume is shown as a function of time. By observing this output, the operator can predict when to expect a slug having a sufficient volume of a desired fluid component, e.g., oil.

[0023] Returning to Figure 1, an operator at the surface monitors the output of the fluid type analyzer *120* and the pressure at the entry port *110* of the flow line *108*, the hydraulic pressure of the pump *200*, and the stroke direction of the pump *200*. The operator uses this information to determine when to open the sample chamber *122* to capture the desired slug. The volumes of most types of sample chambers are significantly smaller than the volume of one pump stroke. Thus, it should be possible to capture enough low-contamination hydrocarbon slug into a sample chamber even when there is still significant amount of mud filtrate contamination. This capability will significantly shorten sampling times. The operator can time opening of the sample chamber *122* to avoid capturing as much as possible of any unwanted fluids. For example, if a single-phase oil sample is desired, and free gas is also slugging out of the pump *200*, the operator can time

opening and closing of the sample chamber *122* to avoid capturing the gas. The main and dead volumes in the fluid analyzer *120* output are observed to see if the slug leaving the pump is single phase or two phase. The dead volumes are observed to see if the slug leaving the pump contains free gas.

[0024] Fluid sampling involves establishing communication between the formation *104* and the entry port *110* of the flow line *108*. Once communication is established between the formation *104* and the entry port *110*, the pump *200* draws fluid into the inlet flow line *108a* through the entry port *110* and sequentially dispenses slugs of individual fluids into the outlet flow line *108b*. The slugs move in trains through the fluid analyzer *120*. In general, the slugs move at the speed of the most viscous phase. As the slugs move through the fluid type analyzer *120*, they are detected and analyzed by the fluid type analyzer *120*. The operator monitors the output of the fluid type analyzer *120* to determine the fluid type of the slugs produced by the pump *200*. From the output, the operator can predict when a slug having a desired fluid is leaving the pump *200*. This also allows the operator to determine when to open the sample chamber *122* to capture the desired slug.

[0025] To capture the desired slug, the operator opens the sample chamber *122* and closes the exit port *112* of the flow line *108* at approximately the same time. Then, the operator starts pumping fluid through the flow line *108*. If the exit port *112* is closed and the sample chamber *122* is successfully opened, the fluid in the flow line *108* will be diverted into the sample chamber *122*. As soon as the sample chamber *122* becomes full, the pump *200* would experience increasing resistance and the hydraulic pressure of the pump *200* would increase noticeably. At the same time, flow from the formation would basically stop and the pressure at the entry port *110* would build up towards formation pressure. By observing the relationship between volume pumped into the sample chamber *122*, hydraulic pressure of the pump *200*, and the pressure of the fluid entering the flow line *108*, it may be verified that the sample chamber *122* opened successfully and captured fluid pumped from the formation. For a good sample capture, there should be more than one pump stroke between opening of the sample chamber *122* and pressure up, i.e., when the hydraulic pressure of the pump *200* increases noticeably, and drawdown should remain constant. When trying to capture a single hydrocarbon phase, the sample

chamber *122* should be opened somewhere during the pump down-stroke.

[0026] Figure 5 shows an example of a sample capture log. On the right (indicated at *500*) is the output of the fluid type analyzer. On the left (indicated at *502*) is the entry port pressure, pump hydraulic pressure, and pump stroke direction information. Figure 5 shows that the operator opened the sample chamber correctly (*504*), caught the desired slug (*506*), and over-pressured the sample in the sample chamber (*508*). Note how the pressure ramps up when the sample chamber becomes full (*510*). Even after the sample chamber is full, pumping continues until the pump reaches maximum compression capability. Once the operator determines that the sample chamber is full, the operator issues a command to close the sample chamber. The operator then verifies that the sample chamber is actually closed. This verification involves closing the exit port (*112* in Figure 1) and then attempting to pump fluids from above the pump (*200* in Figure 1) to below the pump, i.e., from the side of the pump closest to the sample chamber to the other side of the pump. If the sample chamber (*122* in Figure 1) is closed, high resistance is experienced, and the hydraulic pressure of the pump rises

rapidly to a maximum allowable value (see pressure curve *600* in Figure 6). If the sample chamber is open, the pump will be able to push a volume of fluid equal to the volume of the sample chamber before reaching this maximum value.

[0027] The invention provides one or more advantages. Using the method and system described above, slugs of individual fluids can be created, and a slug containing a desired fluid can be captured in a sample chamber while slugs containing unwanted fluids can be avoided. This can reduce sampling times in that it is not necessary to wait for the fluid in the flow line to have an acceptable level of contamination before the sample is captured. Whether the sample chamber is successfully opened, sample is captured, and sample chamber is successfully closed can be verified in real time. A record of the capture can be stored for later use. The tool can be constructed using existing formation tester components, such as included in the Schlumberger MDT.

[0028] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from

the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.